Gail Purvis

One of the most intriguing aspects to the EU *R&D Roadmap for Photovoltaics*, which emerged in 2003, was while there were short to medium research priorities for silicon, no long term priorities were identified (Table 1).

By contrast, for III-V materials (Table 2) new structures η>40% are the first priority, estimated as achievable by 2020. Rather nearer is the priority of a low cost substrate, anticipated by 2010.

LED and nano could boost compound photovoltaics

In the *Photovoltaic R&D Roadmap* findings, compiler and author, Arnulf Jäger-Waldau notes the fact that the price of PVs has to be reduced by at least a factor of two and up to a factor of four or five. For wafer silicon, reasonably priced silicon feedstock was seen as one barrier, manufacturing line throughput the other. For thin films the obstacles are listed as: the poor image of the first amorphous-Si prototypes; low efficiency; short lifetime; safety requirements and cost of production equipment. Yet another sticking point is that PV systems need new electricity storage technology.

But, despite these hampering elements, Si and thin film (TF) Si market shares (Table 3) are anticipated as being close to 95% by 2010, with the CdTe and CIS TF solutions having only 5% market, rising to 15-20% by 2020.

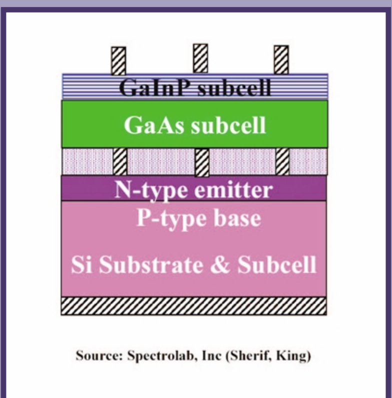

Fig 1 State-of-the-art concentrator cells from Spectrolab Inc.

Table 1 Research priorities for crystalline/multicrystalline silicon.

Issue	Ready	Priority
High-throughput sheets yield, rear passivation BSR	2006	1
Thin wafers (slicing, processing)	2005	2
Low-cost surface passivation	2007	3
Low-cost bulk passivation	2006	3
High-throughput processing	2007	3
Alternative encapsulants	2008	4
Attractive grid designs	2004	4
In-line characterisation	2004	5
Recycling of modules and BOS	2010	5

"The most promising materials for compound semiconductor solar cells are cited as CdTe and Cu(In, Ga)S,Se often abbreviated as CIS (Fig 4). Both materials are in the pilot product phase, still struggling with the not-trivial problems of scaling up module size and production.

"To reach the 20% anticipated market share in 2020, issues such as public acceptance of cadmium and the availability of raw materials have to be solved," adds Jäger-Waldau. As for novel device research priorities (Fig 5) little is anticipated before 2007, with most running at 2015 and 'interface understanding' put as far out as 2020.

But there are some brighter angles that could have an interesting impact on compound PV. The increasing focus on 'new lighting' in the form of LEDs sees a thoughtful parallel drawn between PVs and LEDs by the US National Renewable Energy Laboratory (NREL).

At a National Center for Photvoltaics and Solar Programme Review Meeting in 2003 Dr Sarah Kurtz and later Dr Jeffrey Nelson, CTO, Uniroyal Optoelectronic focused on LED/ PV synergy in R&D and manufacture.

The PV and LED markets show that both industries are currently sized at around \$2-2.5bn. Berkely Laboratories claims that PVs and LEDs are one family, since Berkley Labs researchers in the Materials Sciences division, working with Cornell and Japan's Ritsumeikan Universities in 2002 demonstrated that the bandgap of indium nitride was not 2 electron volts (2eV) as thought, but a much lower 0. 7eV. A low band gap for InP means that an InGaN system of alloys ($In_{1-x}Ga_xN$) covers the full solar spectrum. So a single system of alloys incorporating these can convert virtually the full spectrum of sunlight – from near infrared to the ultraviolet – to electrical current. $Ga_{0.5}In_{0.5}P/GaAs/Ge$ cells are used for space applications and investigated for concentrator applications. High-brightness LEDs are currently fabricated from $Al_xGa_{0.5-x}In_{0.5}P$ or $Ga_{1-x}In_xN$.

For both diode technologies (usually p-n junctions) carriers are confined to an active region. The PV cell generates electricity when light is absorbed and the photocarriers are collected and used as electricity in an external circuit.

Concentrator cells (Fig1) made the news in June when NASA Glen Research Centre, Boeing and Entech produced a concentrator array providing over 200W/m^2 power output at 600V. Located near to the summit of Haleakala volcano on Maui, Hawaii, this used 240 Spectrolab GaAs P/N cells and reached 670W. Typical output is quoted at 16kW/day.

Promising improved solar power generation in space, it also demonstrates that future earth concentrator arrays based on triple-junction GaInP/GaAs/Ge cells could achieve excellent performance at affordable prices.

The LED works in reverse to a PV cell. Carriers are injected and then emit light when they recombine radiatively, and it is common practice to forward bias direct-gap PV cells (making the cell act as an LED for illumination.) Dark or bright spots then indicate a defect and can isolate the origin of shunting of a cell. According to Kurtz, this is a good example of how technology similarities can be exploited. Both PVs and LEDs struggle to achieve high efficiencies a low cost and demonstrate reliability.

While cost breakdowns on LED products are not readily available, for III-V solar cells, substrate and epitaxial growth may be about $210 per 4" Ge wafer (assuming 90% yield and 10µm/hr growth rate.) Used as a rough estimate of substrate cost and epi growth for GaInP LED, it translates to 3cents/mm^2.

Parallel growth of the III-V PV and LED industries could help bring down costs for both. Again reliability, excellent heat sinks, current conduction and light transmission suggest that progress in these is likely to be transferable between sectors.

From LEDs being enabling for PVs in stand-alone, low-wattage applications, to PVs and LEDs sharing similar inverters or drive circuits weakness in systems, Kurtz says that the similarity between R&D issues provides numerous opportunities by which both may learn from each other, while a new breakthrough in either application should be beneficial to the other.

Dr Nelson identifies that the biggest overlap and need for exchange is in concentrator technologies; encapsulation, anti-reflection coatings and passivation; automated visual inspection; thermal-mechanical modelling and design; wafer bonding and substrate release; MOCVD source efficiencies; reactor modelling; in situ diagnostics and the issue of reliability physics.

"There are a growing number of research groups world-wide, that are currently developing concepts to overcome [energy conversion] limitations, eg. intermediate band cells, up, down conversion etc," writes Jäger-Waldau, noting "It is remarkable that, by applying independent and different theories, these groups estimate the ultimate efficiency limit for PV cells to be near 85%." In calling for "a long term, continuous and stable research programme over the next 20 years," the

A cantilever epitaxy substrate allows growth GaN on etched sapphire substrates at Sandia National Laboratories. Reducing dislocation density, the process improves LED performance and is being developed for high-electron-mobility transistors (HEMT) and compact UV emitters (Photo by Randy Montoya).

Table 2 Research priorities for III-V materials.

Issue	Ready	Priority
Low-cost substrate	2010	1
New structures η>40%	2020	1
High-throughput deposition	2015	2
Low-cost concentrators	2007	3
Thermo photovoltaics	2010	3

Table 3 Estimated market shares of different solar cell technologies for the next 20 years.

Material	Market share in year		
	2000	2010	2020
c-Si and mc-Si	~90%	80-90%	~50%
TF silicon (a-Si; mc-Si)	~10%	~10%	20%
Concentrator devices	n.a.	~5%	10%
CdTe and CIS TF	<1%	~5%	15-20%
Novel devices	n.a.	~2%	~5%
Production volume	0.3	3.0	12.4

Photovoltaic drives power new control assembly patent

Morningstar Corp was award a US patent for its new method of assembling power components to thermal heat sinks.

The technology was recently developed and used for the first time in the company's new TriStar solar controller, which has numerous potential applications in power electronics.

It involves a unique methodology for maximising contact between field effect transistors (FETs) and a heat sink, resulting in improved heat dissipation within a smaller configuration. Other benefits include reduced assembly costs, easier troubleshooting and repairs. Morningstar developed its technology in response to difficult design challenges in its new TriStar solar controller.

TriStar wanted power dissipation up to 4kW in 45°C ambient temperature, constrained mechanical specs to allow mounting on power panels, and a very limited cost budget. The engineers met all of these requirements by employing this new FET contact design.

Table 4 Research priorities for CdTe and CIS.

Issue	Ready	Priority
High-throughput deposition (m-Si) process and equipment	2006	1
TCO low-cost, texture	2006	1
Understanding of interfaces	2015	1
Understanding of structure (short and long range)	2015	1
Flexible (plastic) substrates	2008	2
In-line characterisation (uniformity)	2006	3
In situ shunt detection (and repair)	2005	3
Packaging (humidity)	2005	3
Equipment standardisation	2015	3
General stability of device	2010	4
Patterning technology	2005	5

Table 5 Research priorities for novel devices.

ISSUE	Ready	Priority
Collection of generated carriers (lifetime, charge separation mobility, distance)	2007	1
Microstructure (processing, stability)	2010	1
Low-cost materials and processing non-vacuum (e.g. printing)	2015	1
Suitable materials for bandgap engineering	2015	1
Understanding of interfaces	2020	2
Stability (oxidation)	2006	3

roadmap is still optimistic on the issue of third-generation PVs.

ZnO, ITO, FeSiAr[8] and PbS:CdS

The emergence of new materials research, work on hybrids, and a focus on quantum dots and wells may well be the sector that finally carries through the needed energy conversions. As an example of hybrid work Japan's Tokyo University is incorporating stacked Ge islands in the intrinsic layer of Si-based pin solar cells to use light with longer wavelength than the band gap of Si.

Thin film compound and nano structured materials for photovoltaics find a wide range of developments.

Armenia's Yerevan State University Department of Radiophysics and NREL have grown compositionally graded InAsP and lattice-matched quaternary InAsSbP expitaxial layers on an InAs substrate, using a modified version of liquid phase electroepitaxy. It allows growth of high-performance diode heterostructures for mid-IR photodetectors and TPV devices.

A different slant comes from Valencia Polytechnic University and Morocco's University Hassan II, which focused on ZnO. The researchers took the route of ZnO nanocolumns obtained by electrodeposition on GaN substrates. Sizes and surface-volume ratios of the ZnO columns depended on growth parameters. Intense UV emission depends on post annealing treatment. Heteroepitaxial GaN substrates give perfectly oriented ZnO columns of high dimension. Electrodeposition gives quality textured ZnO film for PV use.

From the Department of Renewable Energy, Madrid, the approach (Fig 2) is the use of a ZnO buffer, sputtered before Indium Tin Oxide thin film creation, showing nearly double crystallite size and less than half electrical resistivity than that obtained for ITO on bare substrates, but maintaining high optical transmittance.

At the PV Institute, Forschungszentrum Jülich GmbH, Germany, the target has been doping concentration for ZnO:Al sputter deposition applied as the major parameter to govern the electronic transport needs, as well as the optical properties. This confirms that high-quality ZnO:Al films can be obtained using RF, DC as well as Magnetron sputtering.

Going along the new material track, Surrey University has demonstrated the micro-structural and optical properties of amorphous iron disilicide, a promising semiconductor. Obtained by ion-beam mixing of Fe layers on Si, with Ar^8 ions at 300°C, optical absorption measurements indicate a direct bandgap of 0.88 eV. It should be possible to synthesise this by other techniques, apply it in large-area electronics, and evaluate it for its basic optical properties, which are highly suited for an efficient solar cell.

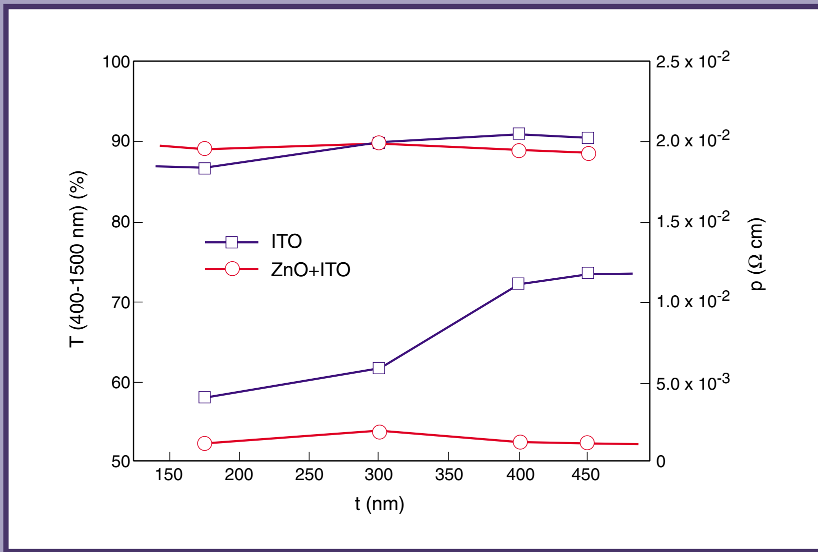

Fig 2 Evolution of ITO transmittance and resistivity for individual and stacked layers with increasing thickness 'Thin Solid Films' ***(451-452)*** *22 March 2004.*

Since this material can be formed without going through a crystalline phase, is synthesised at very low temperatures and is non toxic, cheap and widely available, it is being pursued.

"Next step," says Dr Kevin Homewood, "is the development and evaluation of a suitable p- and n- type doping strategy, so we can make devices." A new PhD student is dedicated to the task from September and Homewood is working to obtain research funding.

Across the globe, Queensland University is taking a quantum composite PV approach, opting for PbS:CdS as a strong UV absorber, with a tunable band gap, control of size distribution by molecular-weight filtration and a long life. Combining PbS QDs with MEH-PPV gives researchers the composite MEH-PPVPbS which will join battle for a winning place in the next generation PV materials.

Space will always afford to pay and rank tops in PV efficiencies, but nano, LED and compounds may be about to start on a new era of new PV materials with mass market potential.

High-efficiency, concentrator PV & novel concepts

The key PV efficiency and concentrator companies identified by NREL are Amonix, Spectrolab, Emcore, Sunpower, Entech, and Solar Research Corp (Australia).

Manufacturability has demonstrated low concentration line focus, high concentration point focus, and high efficiency cells (Si, GaAs multijunctions in production.)

Despite limited applications in today's markets, for hydrogen generation the match may be good. Efficiencies are cited at around 27% for Si (up to 400x) 28% GaAs (up to 1000x), 32.03% $GaInP_2GaAs$ (1x), 30.2%$GaInP_2/GaAs$(180x) and 36.9% $GaInP_2/GaAs/Ge$ (40x600x).

Best prototype modules go to 20% for Si, 24% for GaAs, and 28% for$GaInP_2/GaAs/Ge$. The large-space market drives $GaInP_2/GaAs$ and GaInP/GaAs/Ge commercial cell production. This year Sharp claimed 36.5% efficiency with its InGaP/InGaAs/Ge cell and Spectrolab, the Boeing subsidiary, enjoyed 36.9% efficiency with its terrestrial concentrator cell, from work on lattice-mismatch and matched structures.

NREL identifies the players in new concepts, excitonic devices and new materials as GE Energy, Kodak, Konarka, NanoSolar, Nano Sys, Luna, and UltraDots.

It is interesting to note that one in three nano PV start-ups and spinoffs influenced by the Top Nano 21 are in the compound sector, namely Solaronix SA (Aubonne) with nanomaterials for high efficiency and low cost Cu(In, Ga)Se_2 thin film solar cells.

VHF-Technologies SA (Le Locle) has optical nano gratings for nano crystalline silicon solar cells, while Greatcell Solar SA (Yverdon) works on nanoparticulate semiconductor electrodes for dye solar cells and highly efficient nano crystalline solar cells for indoor applications.

http://www.temas.ch/nano/nano_homepage.nsf